Decaying light particles in the SHiP experiment. II. Signal rate estimates for light neutralinos

D. Gorbunov*
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia and Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia

I. Timiryasov†
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia and Physics Department, Moscow State University, Vorobievy Gory, Moscow 119991, Russia

Considering the supersymmetric models with light neutralino and R-parity violation, we perform estimates of the signal rate expected at the recently proposed fixed target SHiP experiment exploiting the CERN SPS beam of 400 GeV protons. We extend the existing studies by introducing new production channels (in particular through the beauty mesons) and decay modes. We also constrain the model parameter space from analysis of negative results of the CHARM experiment.

I. INTRODUCTION

Supersymmetric (SUSY) extensions of the standard model of particle physics (SM) provide taming of the radiative corrections to the Higgs boson mass (for a review see [1]). The crucial role is played by the superpartners of the SM particles, whose contributions cancel the quadratically divergent quantum corrections of the SM particles. Therefore, one naturally expects to observe (some of) the superpartners at the TeV mass scale. Testing this prediction is one of the main tasks of run 2 at the LHC.

However, there can be *renegades* in the SUSY world with masses (much) below the TeV scale and sufficiently suppressed interactions with the SM fields, so they are missed by numerous previous searches and are beyond the reach of the LHC. The renegade hunting can be performed at a beam-dump experiment, where the high statistics of proton(electron)-proton collisions might compensate for smallness of the couplings, so the new light particles can be produced. Recently a proposal has been submitted [2, 3] to build the new experiment at CERN with a 400 GeV SPS proton beam. Originally motivated as a facility to search for sterile neutrinos (heavy neutral leptons) of $\mathcal{O}(1)$ GeV mass [2, 4, 5], lately it has been recognized as a universal tool to probe various models predicting light, sufficiently long-lived, neutral particles; it has been named SHiP (Search for Hidden Particles) [3]. The SHiP physics case is presented in a separate paper [6], including a number of the SUSY renegades.

In this work, we consider the light unstable neutralino in supersymmetric models with R-parity violation (for reviews, see [7–9]). R-parity is a discrete multiplicative symmetry ascribing factor,

$$R_p = (-\mathbf{1})^{3B+L+2S}\,, \tag{1}$$

to any particle of baryon charge B, lepton charge L, and spin S. All SM fields (including scalars of the extended Higgs sector) have $R_p = +1$, while their superpartners have $R_p = -1$. If R-parity is conserved, superpartners may only be created in pairs. R-parity guarantees stability of the lightest supersymmetric partner (LSP) which becomes a candidate to form the dark matter component of the Universe.

However, the theoretical grounds of R-parity have been questioned (see, e.g., Refs [10, 11]), and one can introduce R-parity violating (RPV) terms in the Minimal Supersymmetric extension of the SM (MSSM). These terms trigger decays of superpartners into SM particles, in particular, decays of the LSP. The latter may be the lightest mass eigenstate in the sector of neutral fermion superpartners called neutralinos. If the neutralino is sufficiently light, it is an example of the renegades to be searched for at the SHiP experiment. There, the neutralinos can be produced either directly in proton scattering off the target material or indirectly via decays of secondary hadrons, and they later decay into SM particles exhibiting signatures very similar to those of sterile neutrinos [4]. Thus, the procedures applied in data analysis to probe both models are very similar. The difference between the two models is expected in the production channel pattern and in decay channel patterns, so that the momentum spectra of each final state and the weights of the different final states ($K^{\pm}\mu^{\mp}$, $\mu^+\mu^-\nu$, etc) are generically not the same in the two models.

Light neutralino phenomenology has previously been studied in the SHiP physics paper [6]. Here, we considerably extend this study by including more production (from neutral charm mesons and from beauty mesons) and decay ($\pi^{\pm}l^{\mp}$, $l^{\pm}l^{\mp}\nu$) channels and by obtaining limits on the model parameter space from analysis of the published results of the CHARM experiment [12, 13].

The paper is organized as follows. In Sec. II we introduce the model and calculate the neutralino production rates and decay rates for a number of channels. In Sec. III we give the estimate of the number of signal events expected in the SHiP fiducial volume. In Sec. IV we present the sensitivity of the SHiP experiment to the model parameters (assuming zero background) and find new limits

* gorby@ms2.inr.ac.ru
† timiryasov@inr.ac.ru

on the model parameters from the published results of the CHARM experiment. We summarize in Sec. V.

II. SUPERSYMMETRY WITH RPV: PRODUCTION AND DECAYS OF LIGHT NEUTRALINOS

R-parity is explicitly violated by the following terms in the MSSM superpotential

$$W_{\not{R}_p} = \lambda_{ijk}\epsilon_{ab}L_i^a L_j^b E_k^C + \lambda'_{ijk}\epsilon_{ab}L_i^a Q_j^b D_k^C \qquad (2)$$

$$+\lambda''_{ijk}\epsilon_{\alpha\beta\gamma}U_i^{C\,\alpha}D_j^{C\,\beta}D_k^{C\,\gamma} + \mu_i\epsilon_{ab}L_i^a H_U^a\,, \qquad (3)$$

where dimensionless couplings λ_{ijk} and mass parameters μ_i (i, j, k run over the three matter generations) characterize violation of R-parity, the superscript C refers to the charge conjugated fields, indices $a, b = 1, 2$ indicate the $SU(2)_W$ doublet components (L and Q are lepton and quark doublets; E, D, and U are lepton , down-type, and up-type quark singlets, respectively), while α, β, γ count $SU(3)_C$ triplet components; ϵ_{ab} and $\epsilon_{\alpha\beta\gamma}$ are fully antisymmetric 2×2 and $3\times 3\times 3$ tensors. Now, if all the terms (2), (3) are present, they initiate the fast proton decay. This process can be forbidden with some discrete remnant of R-parity. In particular, the baryon triality [14] forbids the first term in (3) and hence keeps the proton stable. In what follows we concentrate on the phenomenology of the RPV terms in Eq. (2) and neglect the terms in Eq. (3). Whereas the lightest neutralino should be heavier than 46 GeV in the constrained MSSM with five parameters [15], the authors of Ref. [16] show that this bound can be relaxed and, even a massless neutralino is possible. In this study we consider models with the mass of the lightest neutralino in a GeV range.

Neutralinos as the LSPs could be created in decays of heavier sparticles. Missing momentum carried out by the LSP, which escaped from a detector, remains one of the main signatures in collider searches of supersymmetry. The proposed center-of-mass energy of the SHiP experiment $\sqrt{s} = 27.4\,\mathrm{GeV}$ is too low to create heavy superpartners with masses above the electroweak scale, as we anticipate from LEP-II, Tevatron, and LHC run I. One can check that the neutralino direct production in the proton-proton scattering is negligibly low. Therefore, here we study an indirect production of neutralinos in decays of heavy mesons via R-odd couplings λ' in (2). These R-odd couplings also lead to neutralino decays into the ordinary SM particles.

A. Neutralino production in decays of heavy mesons

Light enough neutralinos $\tilde{\chi}_1^0$ can be produced in decays of heavy mesons (charm D and beauty B) provided that we have R-parity-violating coupling λ' as shown in Fig. 1.

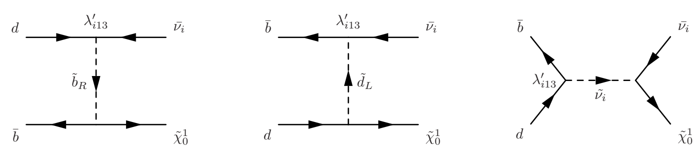

FIG. 1. Typical Feynman graphs of neutralino production in meson decay via R-parity-violating couplings λ'.

Expressions for the partial widths of B_0 and B^+ meson decays can be found in Ref. [17] (for details and derivation of similar expressions see also Ref. [18]). For a neutralino being a pure bino state, they read

$$\Gamma\left(B_d^0 \to \bar{\nu}_i\tilde{\chi}_1^0\right) = \frac{\lambda'^2_{i13}g'^2 f_B^2 M_{B_0}^2 p_{cm}}{128\pi(m_d+m_b)^2}\left[\frac{Y_{\nu_i}}{M^2_{\tilde{\nu}_i}} - \frac{Y_d}{M^2_{\tilde{d}_L}} + \frac{Y_b^*}{M^2_{\tilde{b}_R}}\right]^2 \left(M^2_{B^0} - M^2_{\tilde{\chi}_1^0}\right), \qquad (4)$$

$$\Gamma\left(B^+ \to \ell_i^+\tilde{\chi}_i^0\right) = \frac{\lambda'^2_{i13}g'^2 f_B^2 M_{B^+}^2 p_{cm}}{64\pi(m_u+m_b)^2}\left[\frac{Y_{l_i}}{M^2_{\tilde{l}_i}} - \frac{Y_u}{M^2_{\tilde{u}_L}} + \frac{Y_b^*}{M^2_{\tilde{b}_R}}\right]^2 \left(M^2_{B^+} - m^2_{\ell_i} - M^2_{\tilde{\chi}_1^0}\right), \qquad (5)$$

where p_{cm} is the 3-momentum of outgoing particles in the rest frame of decaying meson, m_u, m_d, m_b are quark masses, m_{ℓ_i} is mass of the final state lepton (electron or muon), $M_{\tilde{\nu}}$, $M_{\tilde{d}_L}$, $M_{\tilde{b}_R}$, … are sfermion masses, Y_{ν_i}, Y_d, Y_b, … are corresponding hypercharges (coming from neutralino couplings in the pure bino limit), g' is $U(1)_Y$ gauge coupling constant, $M_{\tilde{\chi}_1^0}$ is neutralino mass, M_{B^+}, M_{B^0} are B^+ and B^0 masses, respectively, and $f_B = 204 \pm 30$ MeV [15] is the B-meson decay constant. Note that definition of the constant f_B in [17] differs from that by the Particle Data Group [15]. Therefore, formulas from [17] should be multiplied by 1/2 for our choice of f_B.

Without loss of generality, hereafter we assume the common mass scale of sfermions $M_{\tilde{f}} \equiv M_{\tilde{\nu}_i} = M_{\tilde{d}_L} = \cdots = M_{\tilde{b}_R}$ This assumption simplifies further phenomenological treatment since Eqs. (4) and (5) turn into:

$$\Gamma\left(B_d^0 \to \bar{\nu}_i \tilde{\chi}_1^0\right) = \left(\frac{\lambda'_{i13}}{M_{\tilde{f}}^2}\right)^2 \frac{9 g'^2 f_B^2 m_{B^0}^2 p_{cm}}{512\pi (m_d + m_b)^2} \left(M_{B^0}^2 - M_{\tilde{\chi}_1^0}^2\right), \tag{6}$$

$$\Gamma\left(B^+ \to \ell_i^+ \tilde{\chi}_i^0\right) = \left(\frac{\lambda'_{i13}}{M_{\tilde{f}}^2}\right)^2 \frac{9 g'^2 f_B^2 m_{B^+}^2 p_{cm}}{256\pi (m_u + m_b)^2} \left(M_{B^+}^2 - m_{\ell_i}^2 - M_{\tilde{\chi}_1^0}^2\right) \tag{7}$$

and the production rates of neutralinos are proportional to the squared combination $\lambda'_{i13}/M_{\tilde{f}}^2$. Note that our assumption is not related to any particular pattern of mass spectrum of RPV SUSY. In a more general case of different masses of superpartners, the dominant contribution will come from the intermediate sfermion with the highest value of $\lambda'/M_{\tilde{f}}^2$, e.g., from the lightest sfermion, if all RPV couplings are of the same order.

Expressions similar to (6) and (7) can be obtained for decays of D mesons with obvious replacement of couplings $\lambda'_{i13} \to \lambda'_{i21}$ and replacement of the corresponding quark flavors.

B. Decay pattern

We study three different decay channels of light neutralinos with two charged particles in the final state: three-body leptonic decay via λ_{ijk}, two-body semileptonic decay into a charged pion via the coupling λ'_{i11}, and two-body semileptonic decay into a charged kaon via λ'_{i12}. These states yield the detectable at SHiP signature of two charged particles originated from a single vertex.

The amplitude of the leptonic neutralino decay through a virtual slepton or sneutrino was calculated in Ref. [19]. The decay width in the pure bino limit (neglecting masses of the final-state particles) reads

$$\Gamma(\tilde{\chi}_1^0 \to \bar{\nu}_i \ell_j^+ \ell_k^-) = \left(\frac{\lambda_{ijk}}{M_{\tilde{f}}^2}\right)^2 \frac{3 g'^2 M_{\tilde{\chi}_1^0}^5}{4096\pi^3}. \tag{8}$$

The rate of semileptonic decay can be calculated analogously to Eq. (4). In the pure bino limit one has [6]

$$\Gamma(\tilde{\chi}_1^0 \to K^- \ell_i^+) = \frac{9}{256\pi} \left(\frac{\lambda'_{i12}}{M_{\tilde{f}}^2}\right)^2 \frac{g'^2 f_K^2 m_{K^+}^4 \left(M_{\tilde{\chi}_1^0}^2 - m_{K^+}^2 - {m_\ell^i}^2\right) p_{cm}}{M_{\tilde{\chi}_1^0}^2 (m_s + m_u)^2} \tag{9}$$

and the expression analogous to (9) for $\tilde{\chi}_1^0 \to \pi^- \ell_i^+$, which is proportional to $|\lambda'_{i11}|^2$. One can see from Eqs. (8) and (9) that the decay rates of a neutralino, as well as its production rates [Eqs. (6) and (7)], are proportional to the factor $\left(\lambda/M_{\tilde{f}}^2\right)^2$.

If $\tilde{\chi}_1^0$ is produced in decays of D mesons via λ'_{i21} then there is one additional decay channel $\tilde{\chi}_1^0 \to K^0 \nu_i$. A special study is needed to understand whether it can be distinguished from background since there are no charged particles in the final state [20] but it affects the neutralino lifetime. Hence we take into account the decay rate

$$\Gamma(\tilde{\chi}_1^0 \to K^0 \bar{\nu}_i) = \frac{1}{512\pi} \left(\frac{\lambda'_{i21}}{M_{\tilde{f}}^2}\right)^2 \frac{g'^2 f_K^2 m_{K^0}^4 \left(M_{\tilde{\chi}_1^0}^2 - m_{K^0}^2\right) p_{cm}}{M_{\tilde{\chi}_1^0}^2 (m_s + m_d)^2} \tag{10}$$

and a similar one for $\tilde{\chi}_1^0 \to \pi^0 \nu_i$ (which is proportional to $|\lambda'_{i11}|^2$) in further investigations.

III. SIGNAL EVENT RATES

The goal of the present paper is to estimate the event rate of light neutralino decays within the SHiP detector. We consider the light neutralinos created in decays

of heavy mesons. These heavy mesons are produced, in turn, by 400 GeV protons scattering off the target material.

For the production cross section of a particle (a neutralino in our case) with 3-momentum $\vec{p}$ created in a decay of the heavy meson H ($H = D, B$) with 3-momentum $\vec{k}$, one has:

$$\frac{d^3\sigma}{dpd\theta_p d\phi_p} = \mathcal{B}\int d^3k f(\vec{p},\vec{k})\frac{d^3\sigma_H}{dkd\theta_k d\phi_k}, \tag{11}$$

where $p \equiv |\vec{p}|, k \equiv |\vec{k}|$, $\mathcal{B}$ is the branching ratio of H two-body decay to neutralino, $f(\vec{p},\vec{k})$ is the momentum distribution of a neutralino, and $\frac{d\sigma_H}{dkd\theta_k d\phi_k}$ is the differential production cross section of meson H in pp collisions. All the momenta in Eq. (11) are given in the laboratory frame. In the rest frame of the meson H (denoted by an asterisk), neutralino 3-momentum is uniformly distributed and one finds:

$$f(\vec{p}^*, 0) = \frac{1}{2\pi p^*}\delta(p^{*\mu}p^*_\mu - m^2), \tag{12}$$

where $p^{*\mu}$ is the 4-momentum of the neutralino in the rest frame of the decaying meson. Note that the value of $p^* \equiv |\vec{p}^*|$ is fixed by kinematics of the two-body decay. In order to boost expression (12) to the laboratory frame, one should multiply it by the appropriate Jacobian and express $\vec{p}^* = \vec{p}^*(\vec{p},\vec{k})$ in terms of the 3-momenta of the neutralino ($\vec{p}$) and the decaying meson ($\vec{k}$) in the laboratory frame.

The differential cross section of D-meson production in pp interactions at the center-of-mass energy $\sqrt{s} = 27.4\,\mathrm{GeV}$, which is relevant for the SHiP setup, was measured by the LEBS-EHC Collaboration [21]. It has been found that the differential production cross section is well represented by the empirical form [21]

$$\frac{d\sigma_D}{dx_F dp_T^2} = \frac{1}{2}\left(\sigma(D/\bar{D})(n+1)b\right)(1-|x_F|)^n \exp(-bp_T^2) \tag{13}$$

with $n = 4.9 \pm 0.5$, $b = (1.0 \pm 0.1)\,\mathrm{GeV}^{-2}$. We adopt the same value of the inclusive $D/\bar{D}$ cross section $\sigma(D/\bar{D}) = 18\mu\mathrm{b}$ [6]. The differential cross section in (13) depends on transverse p_T and longitudinal p_L components of 3-momenta through $x_F = 2p_L/\sqrt{s}$ and can be related to that used in Eq. (11) as follows:

$$\frac{d^3\sigma_D}{dkd\theta_k d\phi_k} = \frac{4k^2\sin\theta_k}{\sqrt{s}}\frac{d^3\sigma}{dx_F dk_T^2 d\phi_k}. \tag{14}$$

The beauty production cross section has not been measured in the interesting energy region. Therefore, following the SHiP Collaboration [6] we extrapolate existing data [22] to estimate the number of produced B mesons. To estimate the angular distribution of produced B mesons, we employ the theoretical results from Ref. [23] together with the Lund fragmentation model [24].

The probability of $\tilde{\chi}^0_1$ decay inside the fiducial volume of the SHiP detector is

$$w_{\mathrm{det}} = e^{-l_{\mathrm{sh}}/l_{\tilde{\chi}^0_1}}(1 - e^{-l_{\mathrm{fid}}/l_{\tilde{\chi}^0_1}}) \simeq \frac{l_{\mathrm{fid}}}{l_{\tilde{\chi}^0_1}}, \tag{15}$$
$$l_{\tilde{\chi}^0_1} = \frac{p}{M_{\tilde{\chi}^0_1}\Gamma},$$

with l_{sh} denoting the muon shielding length (the distance between the collision point and the detector, 63.8 m for SHiP [3]) and l_{fid} referring to the length of the detector fiducial volume (60 m); the second equality in (15) is valid when $l_{\mathrm{sh}} \ll l_{\tilde{\chi}^0_1}$.

The proposed geometry of the SHiP detector [3] is a 60 m length cylindrical vacuum tank with an elliptical section of x and y semiaxes 2.5 m and 5 m long, respectively. In the following estimates of the signal event numbers, we utilize a more conservative fiducial volume that is a cone formed by the vertex in the target and the 5 m $\times$ 10 m ellipse at the very end of the fiducial volume. It covers part of the elliptical section. We argue that this choice is quite reasonable since neutralino decay products should be tracked by the detector placed at the end of the vacuum tank. We select only neutralinos $\tilde{\chi}^0_1$ with 3-momenta inside the cone region described above.

The number of neutralino decays within the detector is given by

$$N = \frac{N_{\mathrm{POT}}}{\sigma_{\mathrm{pp,total}}}\int_{\mathrm{cut}} w_{\mathrm{det}}\frac{d\sigma_{\tilde{\chi}^0_1}}{dpd\theta d\phi}d^3p \tag{16}$$

where the distribution of neutralinos over the 3-momentum is defined in (11) and "cut" refers to the constraint on the neutralinos' 3-momenta described above and $N_{\mathrm{POT}} = 2\times 10^{20}$ is the number of protons on target during 5 years of operation [6].

We consider the four production channels of light neutralinos described in Sec. II : $D^\pm$, D^0 decays via coupling λ'_{i21} and $B^\pm$, B^0 decays via coupling λ'_{i31}. According to the SHiP technical proposal [3], at least two charged particles are required to distinguish the signal from a background. Hence we consider three decay channels: $\tilde{\chi}^0_1 \to \ell^+_i\bar{\nu}_j\ell^-_k$, $\tilde{\chi}^0_1 \to K^-\ell^+_i$, $\tilde{\chi}^0_1 \to \pi^-\ell^+_i$, driven by λ_{ijk}, λ'_{i12}, λ'_{i11} correspondingly. As a result, we have six combinations of couplings that can be tested by SHiP.

Resulting event rates for neutralinos produced in D^0 and B^0 decays are shown in Fig. 2. Plots for the D^+ and B^+ channels are very similar to those in Fig. 2. At small couplings the number of events drops due to poor production, while at relatively large couplings the number of events also drops because of fast neutralino decay; thus, one has $l_{\tilde{\chi}^0_1} \ll l_{\mathrm{sh}}$ and the neutralino flux in the detector is exponentially suppressed [see Eq. (15)]. The number of events depends both on combination $(\lambda/M^2_{\tilde{f}})^2$ and on neutralino mass. To demonstrate this dependence we solve Eq. (16) with $N \equiv 3$ and find $(\lambda/M^2_{\tilde{f}})^2$ as a function of $M_{\tilde{\chi}^0_1}$. As one can see from Fig. 2, there are two solutions to this equations: one corresponding to small

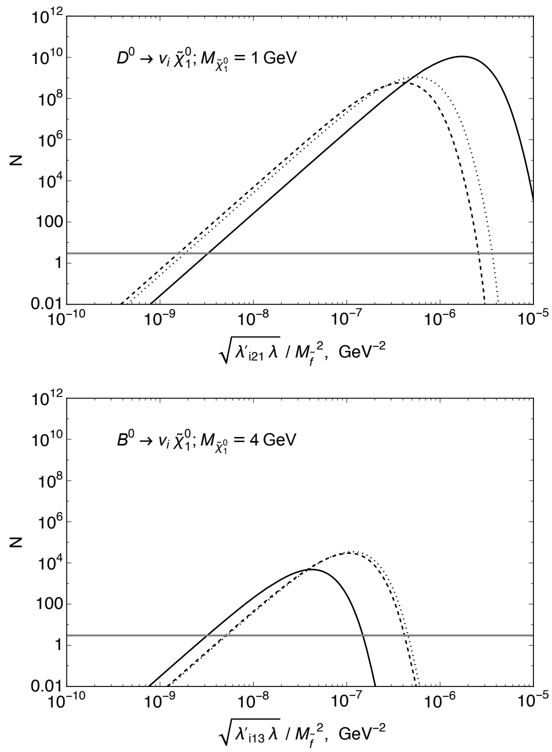

FIG. 2. Number of signal events for neutralinos produced in D^0 decay (upper panel) and in B^0 decay (lower panel). Decays of the neutralino to $e^+\nu_i e^-$ (solid line), to $\pi^+\ell^-$ (dashed line), and to $K^+\ell^-$ (dotted line) are considered. λ stands for the appropriate RPV couplings. The horizontal line represents three events: their absence implies an upper limit on the model parameters placed at 95% confidence level within the Poisson statistics.

couplings and slow decay and another corresponding to relatively large couplings and fast decay. Since large couplings are excluded by different searches (see, e.g., Ref. [7] for details), we show in Fig. 3 a solution corresponding to small couplings. Note that for the small couplings the probability of neutralino decay inside the fiducial volume (15) and, consequently, the number of events is proportional to the decay width. Therefore, one can use Eqs. (4) – (7) and Eqs. (8) – (10) (see also expressions from Ref. [19]) in order to rescale $\lambda'/M_{\tilde{f}}^2$ dependence for the generic case of a nondegenerate mass spectrum and any pattern of RPV couplings.

One can see from Fig. 3 that the decay channel $\tilde{\chi}_1^0 \to K^0\nu_i$ sufficiently affects the lifetime and, subsequently, the event rate of neutralinos created in D-meson decays via the coupling λ'_{i21}.

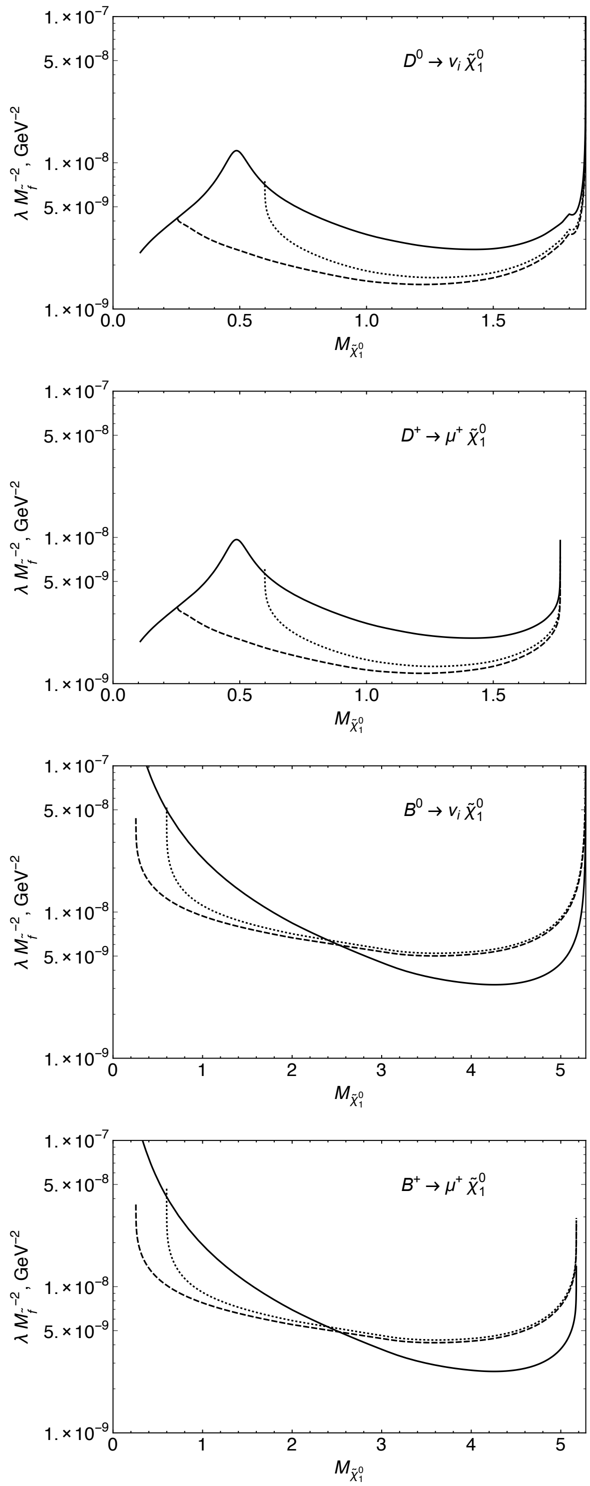

FIG. 3. Expected sensitivity of the SHiP experiment to a light neutralino with RPV. The solid line refers to leptonic decay, the dashed line is for decay to $e^+\pi^-$, and the dotted line is for decay to e^+K^-. λ stands for the appropriate combination of RPV couplings.

IV. SHIP SENSITIVITY TO AND CHARM BOUNDS ON RPV

Absence of the events, while the three signal events are expected, implies 95% confidence level bounds (if background is negligible, which is true in our case [3]). Limits on RPV couplings that could be placed by the SHiP

experiment depend both on the common sfermion mass scale and on the neutralino mass. Exclusion limits on various combinations of RPV couplings are shown in Fig. 4. Dark shaded regions are excluded by previous studies. Namely, the constraints on $\lambda'_{121}, \lambda'_{113}, \lambda_{121}, \lambda_{122}, \lambda_{123}$ have been obtained from charged current universality, and the constraint on λ'_{111} has been obtained from neutrinoless double beta decay (see Refs. [25], [7] for details). Note that these constraints scale as $\propto \lambda/M_{\tilde{f}}$, while in our case of the SHiP sensitivity the scaling goes as $\propto \lambda/M^2_{\tilde{f}}$.

Vertical lines in Fig. 4 at $M_{\tilde{f}} = 1\,\mathrm{TeV}$ show the mass scale that is excluded by the LHC searches in the case of approximately equal sfermion and gluino masses [26]. Note, however, that for some particular RPV spectra this bound can be as low as 800 GeV [27].

We list our estimates of SHiP bounds on these couplings in Table I. As one can see from Fig. 3 the bounds

TABLE I. Estimates of SHiP sensitivity to and CHARM bounds on combinations of RPV couplings. In the first three rows we set $M_{\tilde{\chi}^0_1} = 1\,\mathrm{GeV}$ and $M_{\tilde{\chi}^0_1} = 4\,\mathrm{GeV}$ for the last three rows. Indices $j,k = 1,2$ and $i = 1,2,3$ indicate flavor of the final-state leptons.

λ	Expected sensitivity SHiP, $M^2_{\tilde{f}}/\mathrm{TeV}^2$	Upper limit CHARM, $M^2_{\tilde{f}}/\mathrm{TeV}^2$
$\sqrt{\lambda'_{121}\lambda_{ijk}}$	2.4×10^{-3}	2.5×10^{-2}
$\sqrt{\lambda'_{121}\lambda'_{j11}}$	1.2×10^{-3}	–
$\sqrt{\lambda'_{121}\lambda'_{j21}}$	1.4×10^{-3}	–
$\sqrt{\lambda'_{113}\lambda_{ijk}}$	2.4×10^{-3}	2.5×10^{-2}
$\sqrt{\lambda'_{113}\lambda'_{j11}}$	3.9×10^{-3}	–
$\sqrt{\lambda'_{113}\lambda'_{j21}}$	4.0×10^{-3}	–

listed in Table I are valid for a wide range of kinematically allowed region (with phase-space corrections at the boundaries) of $M_{\tilde{\chi}^0_1}$.

In order to illustrate advantages of the SHiP facility, we also present in Fig. 4 our estimates of the bounds on RPV couplings that follow from the absence of signal in the CHARM experiment. These bounds are obtained by adapting the whole procedure described above for the CHARM geometry [12]. The CHARM experiment has exploited the same 400 GeV beam as the SHiP plans. The detector was located at 480 m downstream from the beam dump. Therefore, it covers a sufficiently smaller solid angle compared to the SHiP. The length of the decay region was 35 m and the radius of the calorimeter placed at the end of decay volume was 1.5 m. The total amount of protons on target equalled 2.4×10^{18} [12]. To the best of our knowledge there was no special investigation of the CHARM sensitivity to RPV SUSY, but very similar signatures of heavy neutral lepton decays to the SM leptons were studied in Refs. [12], [13].

V. CONCLUSION

To summarize, we have estimated the sensitivity of the recently proposed SHiP experiment to the supersymmetric extensions of the SM with light neutralinos and R-parity violation. For the R-parity violating couplings λ of order one, the SHiP will allow us to probe the superpartner mass scale as high as 30 TeV (see Fig. 3), which is in agreement with previous estimates in Ref. [6]. The number of signal events scales as $\propto (\lambda'/M^2_{\tilde{f}})^4$. As a by-product we have obtained limits on the model parameters from nonobservation of anomalous events in the CHARM experiment. With respect to the CHARM, the SHiP will improve the sensitivity to R-parity-violating couplings by an order of magnitude.

Several remarks are in order. First, other final states such as the mentioned neutral kaons must be considered as well. Second, the light neutralinos can be produced in pairs due to R-parity-conserving couplings, and the corresponding new production channels can also be studied. Third, not only heavy meson but also heavy baryons can decay into light neutralinos, which gives additional production channels. Fourth, secondary hadrons, produced in the hadron showers initiated by 400 GeV proton scattering off target materials, can contribute to the light neutralino production. Fifth, τ leptons produced mostly in decays of D_s mesons allow us to probe other R-parity-violating couplings λ_{ijk}, which is also worth investigating.

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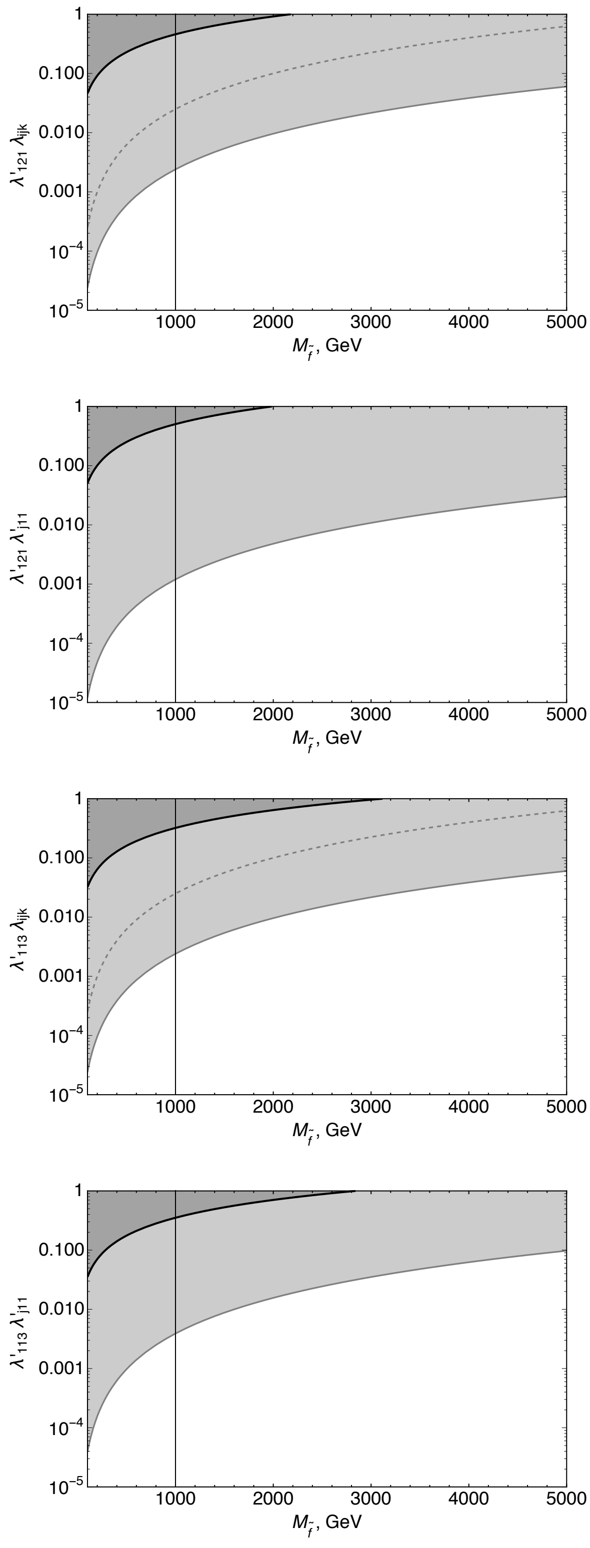

FIG. 4. Bounds on λ as a function of sfermion mass for the light neutralino mass $M_{\tilde{\chi}_1^0} = 1\,\mathrm{GeV}$. The region *above* the thick solid black line has been excluded by previous studies [25], [7]. The region *above* the gray line could be excluded by SHiP data. The dashed gray line corresponds to our estimate of CHARM bounds. The region to the left of the vertical line at $M_{\tilde{f}} = 1\,\mathrm{TeV}$ is generally disfavored as the superpartner mass scale due to searches at the LHC (see discussion in the main text).